An Improved X-Band Maser System for Deep Space Network Applications

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An 8450-MHz (X-band) maser system utilizing a commercial Gifford–McMahon (GM) closed-cycle cryocooler (CCR) was designed, fabricated, and demonstrated. The CCR system was used to cool a maser operating at 8450 MHz. The prototype GM CCR system meets or exceeds all Deep Space Network requirements for maser performance. The two-stage GM CCR operates at 4.2 K; for comparison, the DSN's current three-stage cryocooler, which uses a Joule–Thompson cooling stage in addition to GM cooling, operates at 4.5 K. The new CCR withstands heat loads of 1.5 W at 4.2 K as compared to 1 W at 4.5 K for the existing DSN cryocooler used for cooling masers. The measured noise temperature, T_e, of the maser used for these tests is defined at the ambient connection to the antenna feed system. The T_e measured 5.0 K at a CCR temperature of 4.5 K, about 1.5 K higher than the noise temperature of a typical DSN Block II-A X-band traveling-wave maser (TWM). Reducing the temperature of the CCR significantly lowers the maser noise temperature and increases maser gain and bandwidth. The new GM CCR gives future maser systems significant operational advantages, including reduced maintenance time and logistics requirements. The results of a demonstration of this new system are presented. Advantages of using a GM-cooled maser and the effects of the reduced CCR temperature on maser performance are discussed.

I. Introduction

The Deep Space Network (DSN) currently uses maser amplifiers that are cooled with custom-built Joule–Thomson (JT) cryocooler systems. Maser systems are the lowest-noise microwave amplifiers available. Although maser amplifiers have proven to be quite robust and reliable, the JT cryocoolers are a substantial maintenance problem to DSN operations. This article describes an 8450-MHz (X-band) maser that is cooled to 4.2 K with a commercially available two-stage Gifford–McMahon (GM) cryocooler. The cryocooler enables existing (and future) masers to meet NASA's DSN performance specifications with reduced system implementation, reduced maintenance costs, and extended lifetimes between failure.

The cryocooler is similar to the GM cryocooler used to cool DSN high-electron mobility transistor (HEMT) amplifiers. Using the GM cryocooler will improve the mean time between failure (MTBF) and

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the mean time to return (MTTR) to operation of masers to that of HEMT systems. Existing masers can be retrofitted with the new cryocooler with a simple modification installed at the DSN Complex Maintenance Facilities.

II. The Prototype Maser System

A. Description of the Prototype Maser System

The prototype system is similar to a DSN Block IIA maser [1]. It is cooled with a new commercial GM cryocooler that operates at 4.2 K. The system was constructed using a prototype of the Block IIA maser structure. This maser has a higher noise temperature than the operational masers. The low-noise input, pump source, and the remaining hardware were left over from other projects. A commercial Sumitomo GM cryocooler was borrowed from the 32-GHz (Ka-band) maser program. The maser installed on the cryocooler is shown in Fig. 1.

B. Noise Temperature Measurements

The noise temperature of the prototype maser was measured using the standard DSN total system operating temperature, T_{op}, method with an ambient load and the sky providing temperature references. A standard DSN 22-dB feed horn and waveguide transition was used for the measurement. The measured T_{op} for the system was 12 ± 0.2 K. This translates to a maser input noise temperature of 4.6 deg. A summary of the noise-temperature test is shown in Table 1.

Fig. 1. The maser installed on the GM cryocooler.

Table 1. Noise temperature contribution (8450 MHz).

Noise contributor	Contribution, K
T_{cosmic}	2.5
$T_{\text{atmosphere}}$	3.0
$T_{\text{horn+waveguide}}$	1.5
$T_{\text{follow-on}}$	0.4
T_{maser}	4.6
T_{op}	12.0

C. Performance Advantages of Maser Amplifiers

The key performance characteristics of the GM prototype and the Block IIA are shown in Table 2. The maser structure used for the demonstration performs adequately but is not representative of typical masers in the DSN. The forward loss of this particular maser is substantially higher than normal. The system would meet or exceed all Block IIA specifications with a standard maser.

Although the noise performance of HEMT amplifiers continues to improve, maser amplifiers continue to achieve the lowest noise temperatures of any system installed in the DSN. The typical input noise temperature for all the DSN Block IIA masers produced is 3.8 K. The lowest noise temperature of any X-band HEMT installed on a DSN antenna is 6 K.

Radio frequency interference (RFI) from uplink transmitter power and other sources is a problem in the DSN. Maser amplifiers have a clear advantage for tolerance and rejection of out-of-band RFI. HEMT amplifiers begin to suffer gain compression when the interference signal level reaches −40 dBm. Out-of-band signals as low as −70 dBm can generate intermodulation products that can interfere at the signal frequency.

Table 2. Key performance characteristics of the GM-cooled maser and the standard Block IIA.

Parameter	GM prototype	Typical Block IIA[a]
Equivalent input noise temperature at 8450 MHz	4.6 K	3.8 K
Bandwidth, 3 dB	100 MHz	107 MHz
Maser net gain	38 dB	40 dB
Ruby absorption	21 dB	16 dB
Total forward loss	14 dB	9 dB
Electronic gain	52 dB	49 dB
Inversion ratio	2.47	3.0
Short-term gain stability, 10 s	±0.015 dB	±0.01 dB
Long-term gain stability, 1 h	±0.5 dB	±0.5 dB
Operating temperature	4.2 K	4.5 K

[a] Typical values are from [5].

The prototype maser was tested for out-of-band gain rejection at the DSN transmitter frequency of 7190 MHz by injecting a signal at the input and monitoring the gain at 8420 MHz. The measured gain change due to input power at 7190 MHz is shown in Fig. 2. No effect on the gain was seen at input levels of less than +20 dBm (200 mW). This is a 60-dB or greater advantage over HEMT amplifiers. The change in gain is due to slight heating of the maser structure and not to electronic gain compression. The maser remains linear and does not generate any intermodulation products.

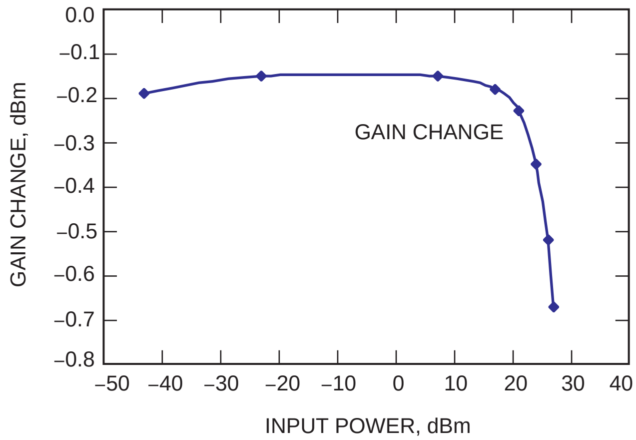

Fig. 2. Measured gain change due to input power at 7190 MHz.

D. Operational Advantages of the GM-Cooled Maser

Maser JT coolers have long been identified as a maintenance trouble area in the DSN. The GM cryocoolers used to cool HEMT amplifiers have proven to be more reliable than the maser JT systems, and the GM cooler used with the maser is expected to perform similarly to the HEMT systems in terms of reliability.

In addition to performance advantages, the GM maser has many advantages in terms of operational logistics and maintenance over the JT-cooled systems. The GM cryocooler system is much smaller and simpler than the JT system. The system consists of the cryocooler cold head in the maser housing, a single-stage helium compressor, and two interconnecting lines. The JT system requires a two-stage compressor, the JT cryocooler, three helium lines, external valve arrangements, a JT flow meter, an external adsorber, a liquid-nitrogen-cooled helium purifier, liquid-nitrogen dewars, and handling equipment. Figure 3 shows the equipment required for the GM cooler as contrasted with the JT system.

JT systems require that the helium return pressure from the liquid-helium bath be maintained near atmospheric pressure. Leaks in the helium lines from this stage of the system can allow air to be introduced into the system, resulting in contamination failures. The GM cryocooler operates at pressure well above atmospheric and will not have this problem.

The time required to cool the system from room temperature to 4 K is reduced with the GM system. The GM maser cools down in 7 hours. The cool down requires no liquid-nitrogen precool. The JT coolers require 12 hours without precool or 7 hours with precool. A plot of the cool-down temperatures is shown in Fig. 4.

There is a significant advantage to avoiding precooling of the systems. In Cassegrain antennas, a worker has to carry nitrogen up the antenna and supervise the precool, which takes 1 to 2 hours. This has been a safety concern of DSN maintenance as well as a station maintenance time concern. Once the GM maser has started cooling, there is no need for an operator to be in the antenna.

Fig. 3. The GM-cooled maser system (left) and the current DSN JT-cooled maser system (right).

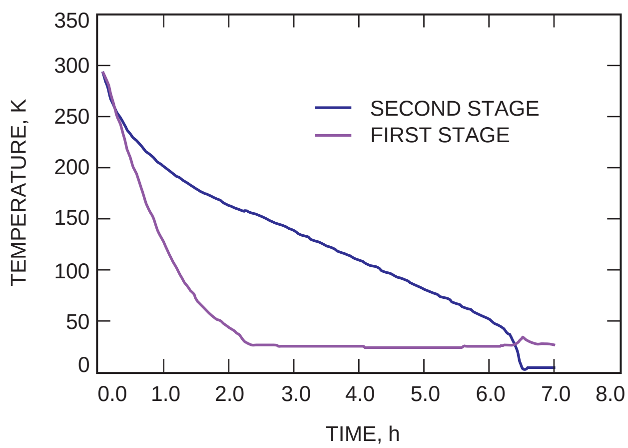

Fig. 4. The GM maser cool-down temperature versus time.

The GM system is also much more tolerant of power failures. Power failures as short as 1 minute can cause JT-cooled masers to warm up enough to cause the superconducting magnet to discharge. Power failures of 5 minutes or more often cause contamination migration in the JT system that requires the system to be decontaminated by warming the system to ambient temperature, purifying the helium gas, and recooling. This process can take 24 hours or longer.

The GM system has demonstrated the ability to stay at operating temperature during a 5-minute power failure and to recover with no magnet discharge. GM cryocoolers are inherently resistant to contamination. The long-term power-failure tolerance was demonstrated by disconnecting the input power for 8 hours and then reconnecting the power. The cryocooler returned to operating temperature in 6 hours with no assistance.

It should be noted that, although this short-term demonstration shows the potential of the new system, there are not enough data to predict the actual reliability in operation.

E. Maser Noise Temperature and Operating Temperature

The physical temperature of the maser ruby material is critical to maser noise temperature. The theoretical noise temperature for a maser amplifier operating at low frequencies as a function of its physical temperature is given in [2] as

$$T_{amp} = \left(\frac{\text{total forward loss, dB}}{\text{net gain, dB}} \right) T_{\text{physical}}$$

Although this approximation is valid at low frequencies, it does not include the quantum noise, T_q. At X-band, this contribution is 0.4 K.

An additional term is required to account for the input transmission-line contribution, T_{in}. The input contribution is assumed to be 0.5 K:

$$T_{\text{maser}} = \left(\frac{\text{total forward loss, dB}}{\text{net gain, dB}} \right) T_{\text{physical}} + T_q + T_{\text{in}}$$

where T_{maser} is the equivalent input noise temperature of the maser referenced to the room temperature input in kelvins. Using the values for the prototype maser from Table 2, the theoretical and measured noise temperatures as a function of physical temperatures are plotted in Fig. 5. Although there is some disagreement between the absolute values of the data, the slopes of the curves are similar. There is a substantial benefit to cooling masers to the lowest possible temperature. The noise temperature of a maser increases nearly 2 K for a 1-K change in cryocooler temperature.

F. Maser Gain and Operating Temperature

Maser amplifiers require a very stable temperature to meet DSN gain-stability requirements. A maser gain reduction of 1 dB occurs for a 0.1 K change in cryocooler temperature. The short-term gain stability requirement for DSN masers is ±0.03 dB over 10 seconds, resulting in a 0.003-K stability requirement for the cryocooler over a 10-second period. The long-term requirement is ±0.5 dB in 1 hour. The measured gain change of the prototype maser as a function of temperature is shown in Fig. 6.

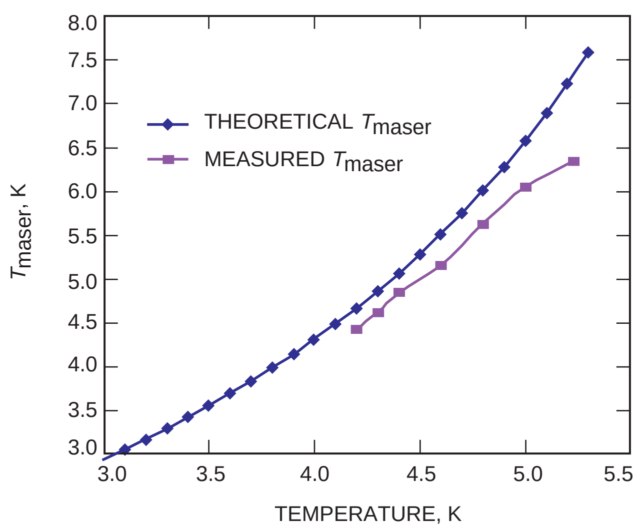

Fig. 5. The maser input noise temperature as a function of physical temperature.

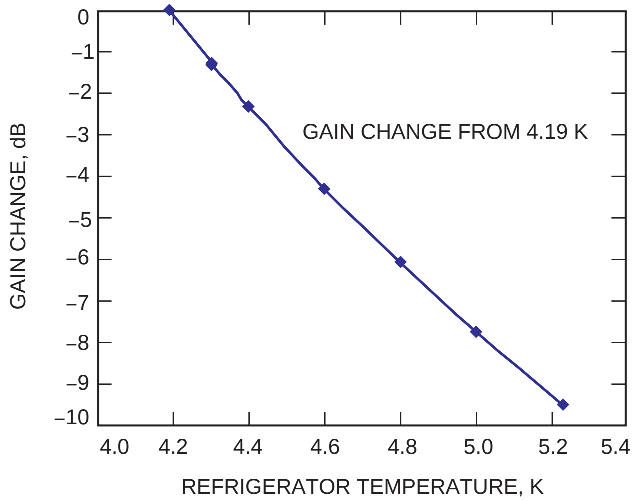

Fig. 6. Gain change as a function of physical temperature.

G. Maser Cryocooler

1. Maser Cryocooler Requirements. Currently, all DSN masers are cooled with JT cryocoolers that are precooled with GM cryocoolers [3]. The cryocoolers have from 1 to 2 W of reserve capacity at 4.5 K. The JT coolers used in the DSN are custom-built devices that are complicated and require specialized skills for fabrication. In addition to the cryocooler, a special helium compressor is required [4]. All of these devices were developed, fabricated, and tested at JPL.

2. GM Cryocoolers. GM cryocoolers were developed in the 1950s and are used in all DSN low-noise amplifier systems. These systems provide two stages of cooling, typically at 50 and 15 K. Recently, 4-K GM cryocoolers have become available from commercial manufacturers. The primary use for these systems has been recondensing liquid helium used in superconducting magnets for medical magnetic resonance imaging (MRI) systems.

Cryocoolers from two commercial sources have been under evaluation at JPL for 2 years. The Sumitomo RDK-415 has been selected as the standard cooler for DSN applications. The first stage of the cooler provides 55 W of cooling at 50 K and 1.5 W of cooling at 4.2 K at the second stage. The measured capacity for the first stage is shown in Fig. 7. The second-stage capacity is shown in Fig. 8.

The biggest challenge to using GM cryocoolers for maser cooling is temperature control. The JT systems currently used provide temperature control by controlling the pressure of the liquid helium in the JT stage. This approach results in millikelvin control of the maser. GM cryocoolers are mechanical heat engines. They exhibit a periodic temperature fluctuation as helium is compressed and expanded at the engine operating speed near 1.2 Hz. Unloaded, the temperature fluctuation is as large as 0.1 K. This is a factor of one hundred higher than required for use with masers.

3. GM Cryocooler Temperature-Control Techniques. In order to meet the gain stability specification, the temperature of the GM cryocooler needs to be regulated. A passive temperature-control system using the thermal equivalent of a resistor–capacitor low-pass filter was developed. It uses a quantity of helium liquid as a thermal capacitor and a stainless steel shim as a thermal resistor.

The value of the shim resistance required was calculated, and the helium volume was adjusted empirically to provide the temperature regulation required. The system provides adequate control of the short-term temperature stability. The measured gain stability of the GM-cooled maser is ± 0.01 dB/10 s

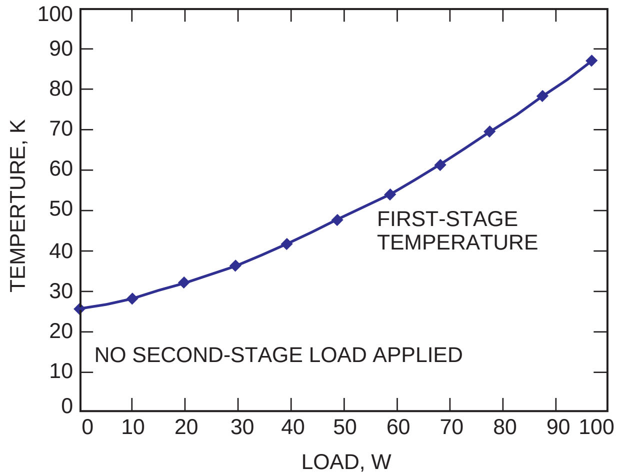

Fig. 7. First-stage refrigeration capacity.

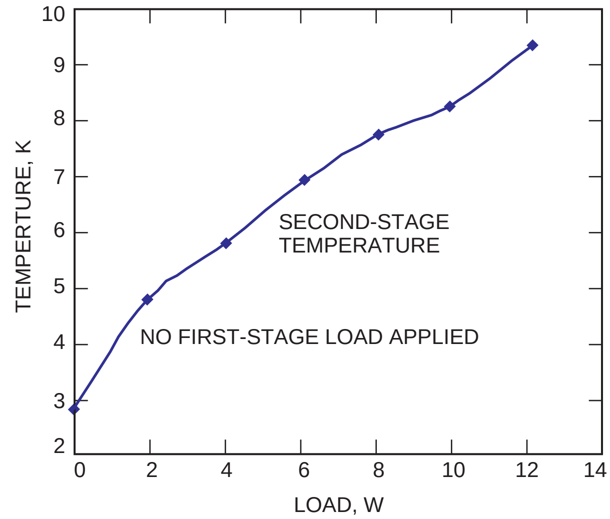

Fig. 8. Second-stage refrigeration capacity.

using the passive regulator, implying a ±0.001-K cryocooler temperature fluctuation. A plot of the operating temperature cycle with regulation is shown in Fig. 9.

Long-term changes in the cryocooler temperature also are a concern. The prototype system uses a commercial temperature controller that adds heat as needed to maintain a constant temperature. A Lake Shore Cryogenics model 340 temperature controller is used for this application. It uses a silicon diode as a temperature sensor and controls a resistance heater with an adjustable proportional-integral-differential controller. The system delivers ±0.003-K control over 1 hour. In addition to controlling the temperature, the controller serves as a real-time refrigeration capacity monitor. The unit displays the percentage of the heater power applied for temperature control. This display is proportional to the reserve refrigeration capacity of the cryocooler.

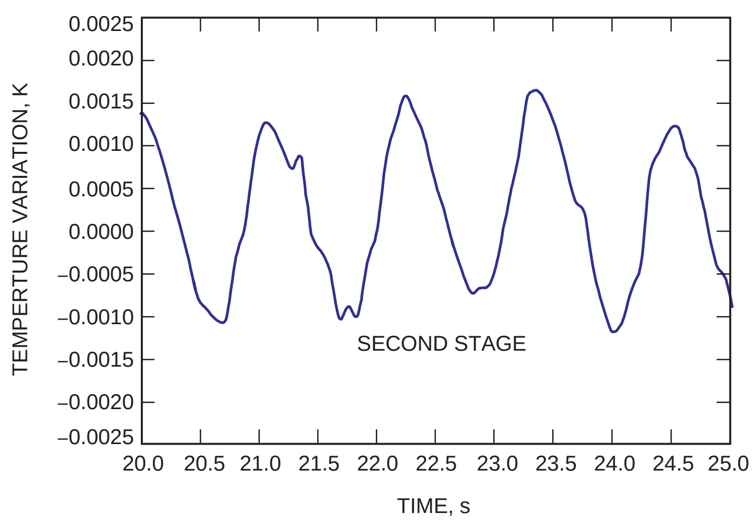

Fig. 9. Cryocooler temperature regulation with a passive regulator.

H. Maser Instrumentation

One disadvantage of maser amplifiers as compared with HEMT systems is the additional instrumentation required to operate the maser. X-band masers require pump energy signals that are swept in frequency near 19 and 24 GHz. The swept frequency range of two Gunn oscillators is adjusted to tune the maser for the proper operating frequency and bandwidth. A superconducting magnet supplies the magnetic field required for maser operation. The magnet requires tuning by adjusting the applied current.

A simple instrumentation system was used to support the prototype testing. It was based on commercial off-the-shelf components and software. The maser instrumentation system is controlled by a laptop PC running LABVIEW measurement and control software. The program provides a single display graphical user interface to control all the maser-tuning functions.

The major hardware component is a Hewlett Packard (HP) modular power supply that provides the pump-tuning voltages, the superconducting magnet current, and the magnet switch. The power supplies are programmable and are controlled using an IEEE-488 interface. Once programmed, the power supplies retain the programmed setting even after the input power is disconnected.

Special instrumentation also was developed for studying the temperature fluctuations of the GM cryocooler. A carbon-glass resistance (CGR) temperature sensor was used. The manufacturer calibrates these devices, which are very sensitive to small changes in temperature. The temperature-resistance curve of these devices is highly nonlinear. In order to get real-time information on the temperature of the cryocooler, it was necessary to compute the temperature of the CGR from a Chebychev polynomial expression provided by the manufacturer.

The temperature instrumentation hardware consists of the CGR sensor, a constant-current source, a programmable voltmeter, and a Macintosh computer with LABVIEW software. Ten measurements per second were taken to analyze the 1.2-Hz fluctuation.

III. Areas for Future Study

The advantages of cooling masers to the lowest possible temperature have been discussed. One problem with the passive temperature-control system is the thermal resistance required between the cryocooler and the maser. The required resistance results in the maser operating at a temperature that is 0.5 K or more higher than the cryocooler. This higher temperature degrades the maser performance in comparison with the maser performance available at the lower temperature.

The predominant effect of a cryocooler temperature change is a change in the maser gain. It may be possible to use an open maser loop-gain controller that will utilize the well-known relationship of maser gain in dB to the maser's physical temperature. Further work should be done on developing a gain-stabilization technique that does not require temperature increase due to the thermal resistance.

IV. Conclusion

An X-band maser cooled with a commercial GM cryocooler was designed and demonstrated. The system meets all the cooling performance specifications of the current maser systems. The lower operating temperature of the cryocooler will result in improvements in maser system-noise temperature, gain, and bandwidth. The GM cryocooler will improve the reliability of masers in the DSN to that achieved with HEMT amplifiers. Maser amplifiers offer significant advantages to the DSN, including lower noise temperature and improved rejection of unwanted signals, as compared with HEMTs.

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